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ENGINEERING SEISMIC INVESTIGATION OF THE VILLAGE OF PAGUATE, NEW MEXICO

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CONTENTS

TABLES

FIGURES

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INTRODUCTION

This report summarizes the investigation of the levels of ground motion in the village of Paguate, New Mexico, associated with contained explosions detonated near an open-pit mine adjacent to the village (fig. 1); it includes both a discussion of the results and preliminary conclusions. A final report will be published pending review of this report by the Bureau of Indian Affairs, the Laguna Council, the Paguate Village Council, and the U.S. Geological Survey.

The objective of the project is to investigate the possibility of building damage from man-made seismic sources, the probable distribution of the induced ground motion, and the areas of high potental risk from vibration damage in the future. The report suggests a procedure to help minimize the possibility of vibration damage to the structures of the village of Paguate, from future local industrial, cultural, or reclamation activities.

Induced ground motions that resulted from eight contained test explosions located near the Jackpile open-pit mine were recorded at 29 locations in the village. The seismic data from the explosions were analyzed to establish the attenuation factors for the induced ground motion, and the site and building responses to the induced ground motion at pertinent locations. Forty test borings and 25 shallow refraction surveys were made within the village to establish the near-surface site geology. The footings of 12 bearing walls of pertinent buildings were exhumed and inspected to investigate the possibility of differential compaction beneath the buildings. Over 95 percent of the buildings in the village of Paguate were inspected and evaluated according to the degree of existing damage. Similar damage inspections and evaluations were made on approximately 50 structures of similar type in two other villages in New Mexico located in geologically similar areas but not near quarries. Bearing walls of 21 buildings in the village of Paguate were tested to document the structures' natural vibration period and percentage of vibration damping.

BUILDING INSPECTIONS AND TESTING

The first step in the investigation was to establish a method to compare and map the building damage in the village. The predominant type of structure in the village is similar to the "Chaco" or prehistoric native type (stone core with mud or adobe outer covering) rather than the "Spanish" adobe-brick type (King and others, 1985; Iowa, 1985). However, buildings built within the village in the last 15 years may be any of the standard wood-frame, "Spanish" adobe-brick, or rehabilitated "Chaco" types. The village building inventory consists of approximately 60 percent of the prehistoric-native type (mud- or stucco-covered "Chaco" type), 10 percent "Spanish" adobe-brick type, and 30 percent wood-frame type (the 25 HUD buildings bias the data toward the wood-frame type). No trailers, temporary, or minor outlying structures were included in the inventory. Less than 5 percent of the buildings are totally native in internal and external construction; for example, most buildings have modern rafter and (or) metal roofs.

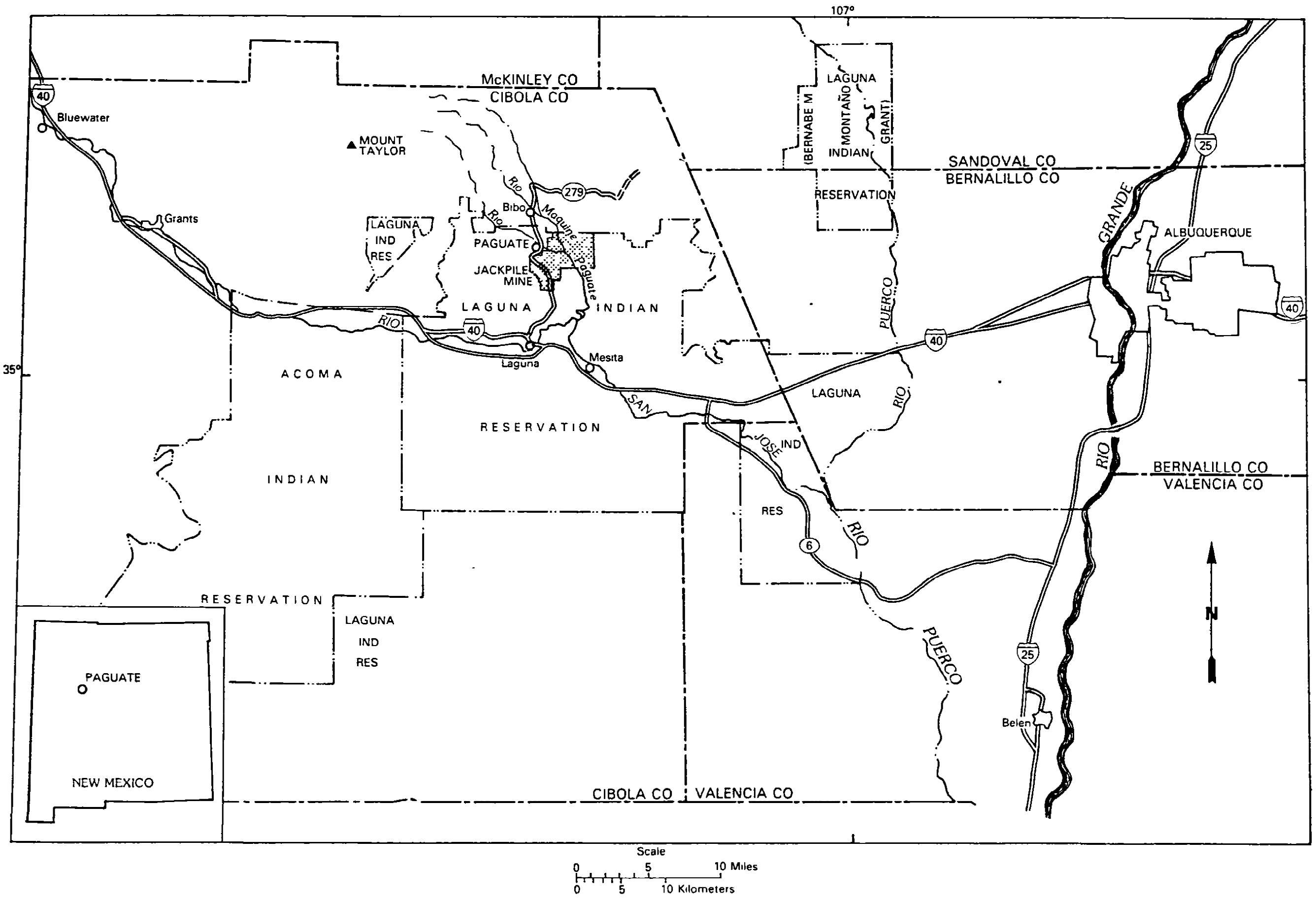

Figure 1.--Map showing location of the Jackpile Mine (shaded) and the village of Paguate, New Mexico.

The measurement or scaling of the degree of damage to the buildings is subjective; however, by sampling more than 90 percent of the major buildings in the village and by having a large number (more than 50 percent) of the buildings inspected and damage scaled by more than one inspector, a workable statistical model and a general building-damage map of the village were obtained. Table 1 shows the scale that was used to categorize the damage, and figure 2 is a map showing the distribution of the building damage. Five buildings were rated at a damage degree of 5, 29 buildings rated a degree of 4, 85 buildings rated a degree of 3, and 52 buildings rated a degree of 2. No buildings were found to have a rating of 1 in the village. The damage ratings assigned to the buildings may vary by one degree; however, all buildings rated at a 4 or 5 were inspected by at least two inspectors at different times to verify their ratings. The damage map indicates that the buildings with higher degrees of damage are not randomly distributed over the village but rather are clustered in specific areas. This map also indicates that buildings with higher degrees of damage (in the northwest and the southwest) are located farther from the mine pit than some buildings with lower degrees of damage, and that the wood-frame houses, in general, show lower degrees of damage than the "Chaco" or adobe types.

The damping and natural resonant frequency of the buildings in Paguate are important parameters in the analysis of the response of the buildings to induced ground motion. Because a large number of the buildings are irregular, nonengineered structures which would be difficult to model, the test procedure for obtaining these parameters generally consisted of installing horizontal, velocity-sensing seismometers on the top-midpoint of bearing walls of the structure (King, 1969). Ambient seismic background and the induced shaking were then recorded (fig. 3). The induced vibrations recorded in this study were from man-induced forces. input in close synchronization with the structure's approximate natural resonant frequency. This technique has been described in detail by Hudson and others (1964) and by King (1969).

The data from the tests were analyzed to determine the response of the walls to induced motions, the natural periods of the walls, and the damping factors of the walls. The data were analyzed to obtain the approximate percentage of critical damping using

$$\beta = \frac{1}{2\pi} \left(-\ln \frac{Xn + 1}{Xn}\right) ,$$

where β is the percent critical damping and Xn is the velocity amplitude for the nth cycle of motion. The natural periods of the walls were picked as the peak of the response spectra (fig. 4). The natural frequencies varied from 3.7 to 18.1 Hz with damping varying from 1.6 percent to 7.8 percent (table 2). The periods and damping values are in the normal range for "Chaco"-type structures (King and others, 1985).

We could not find any nearby villages located away from a quarry, mine, road building, or other blasting activities, that have similar type buildings as Paguate, and that are underlain by 1-20 ft of sediments similar to those that underlie Paguate. The 50 similar-type buildings (30 buildings of "Chaco"-type construction and 20 buildings of mixed-adobe, stone, and stick-frame construction) that were inspected for comparison with those in Paguate are in the villages of San Felipe and Santo Domingo, which are located away from blasting activity. Because these villages are located on a river wash

Table 1.--Damage scale for adobe/rock structures

Degree 1

Light visible cosmetic cracking in the interior and (or) exterior. Cracks less than 1 mm wide.

Degree 2

Visible cracks 2 mm or less wide in the interior and exterior. Fine cracks (less than 2 mm wide) near windows, doors, and support members.

Degree 3

Visible cracks 2-5 mm wide which extend from or connect points of stress. Length of cracks exceeds 10 cm. Erosion of cracks may be present. Light structural damage is possible (ceiling or viga cracking, door or window framing distorted, etc.).

Degree 4

Visible cracks 5-12 mm wide with lengths over 10 cm. Few cracks through width of wall. Large number of cracks 2-5 mm wide. Cracking recurring through past repairs into original construction. Distortion or evidence of movement of structural members. Moderate structural damage present.

Degree 5

Visible damage (cracking, movement, distortion) present on interior and exterior walls. Cracks larger than 5 mm through thickness of wall. Extensive cracks including a moderate number larger than 12 mm wide and exceeding 10 cm in length. Major distortion or movement at stress concentration points (windows, doors, roof supports, wall supports, etc.).

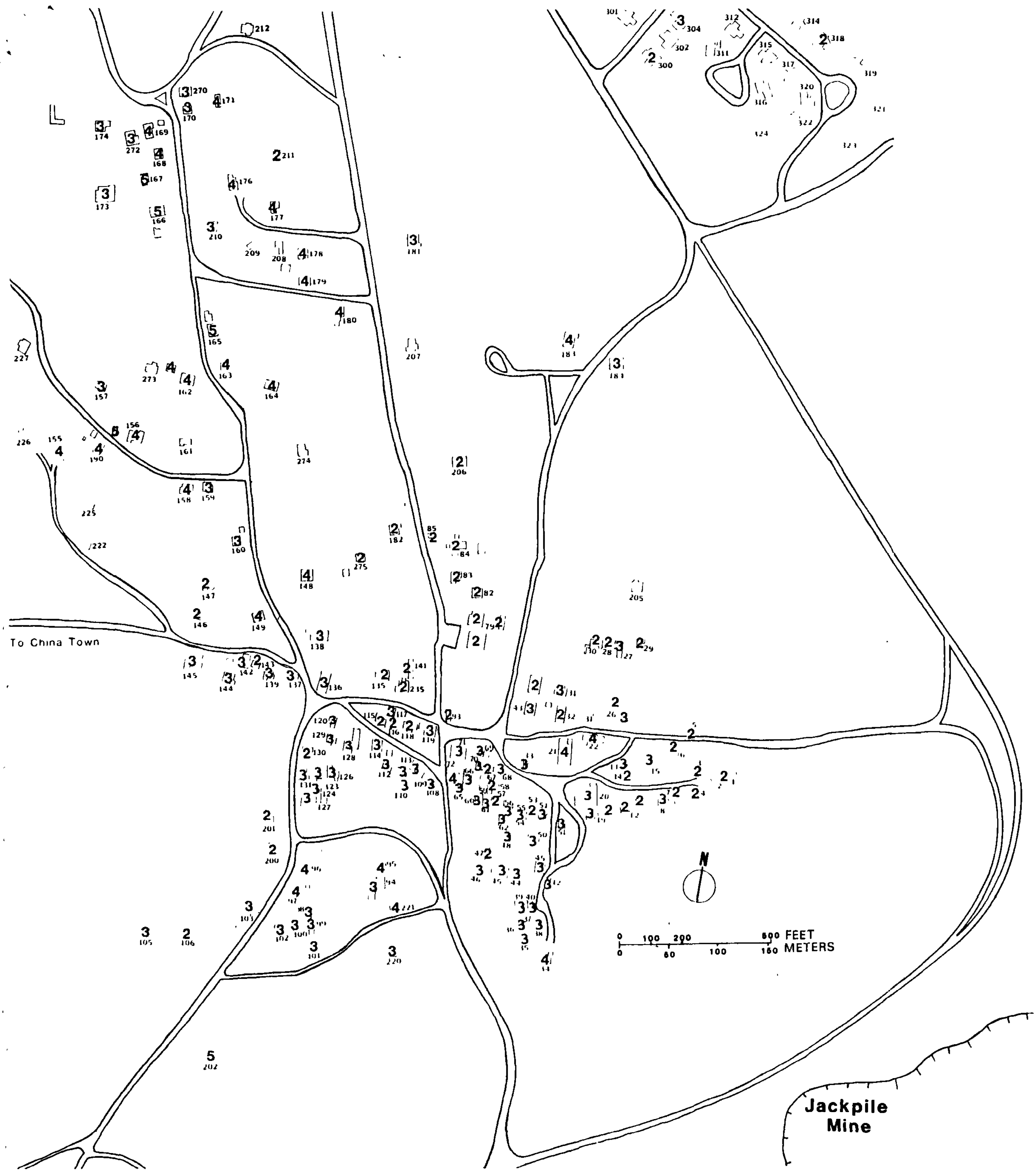

Figure 2.--Map showing the village of Paguate and the distribution of building damage using the scale shown in Table 1. Degree of damage shown by large numbers. Small number adjacent to the building is used to identify that structure in the text.

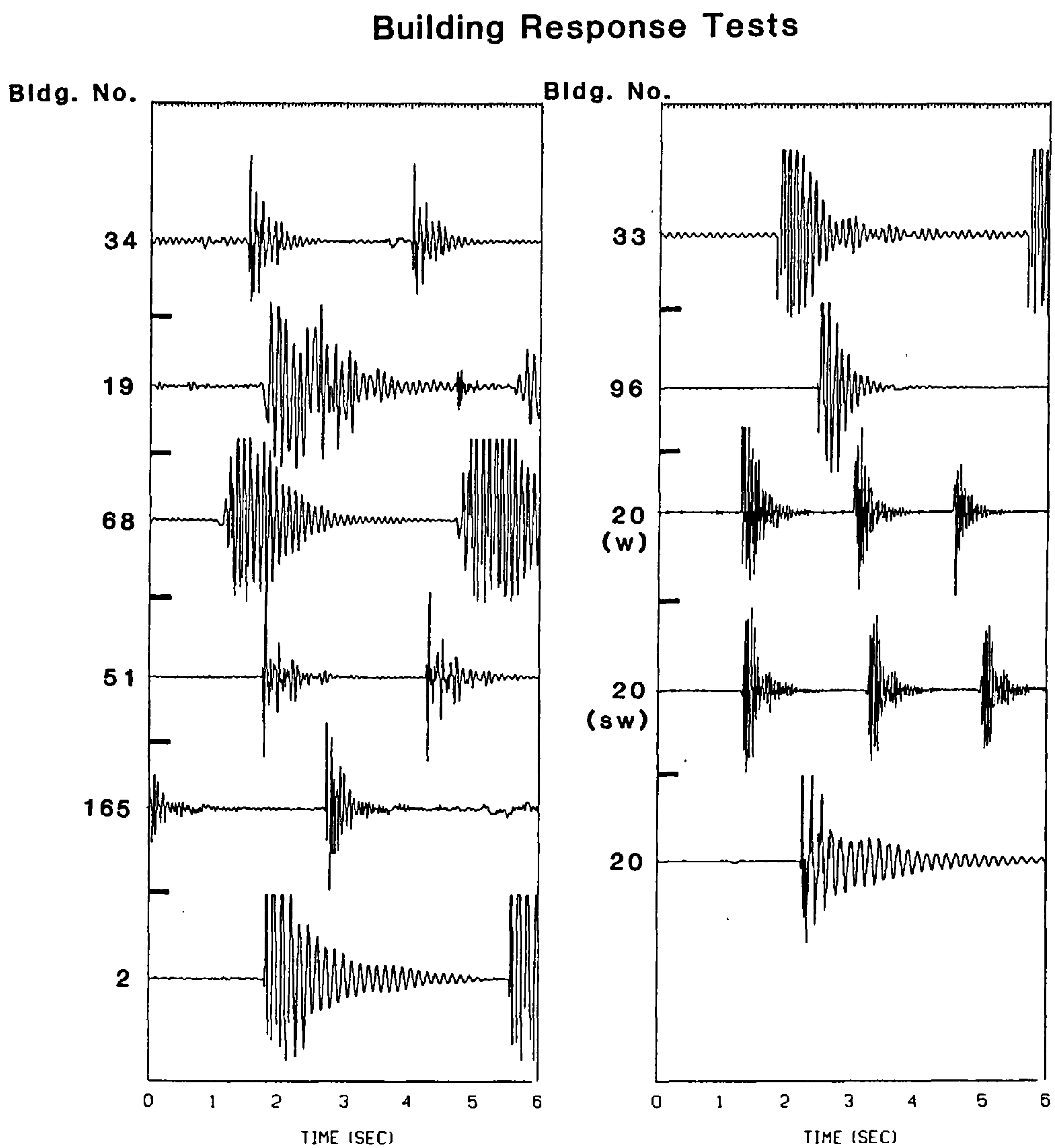

Figure 3.--Time histories for man-induced vibrations measured on the top-midpoint of the bearing walls of the buildings listed to the left of the seismic record.

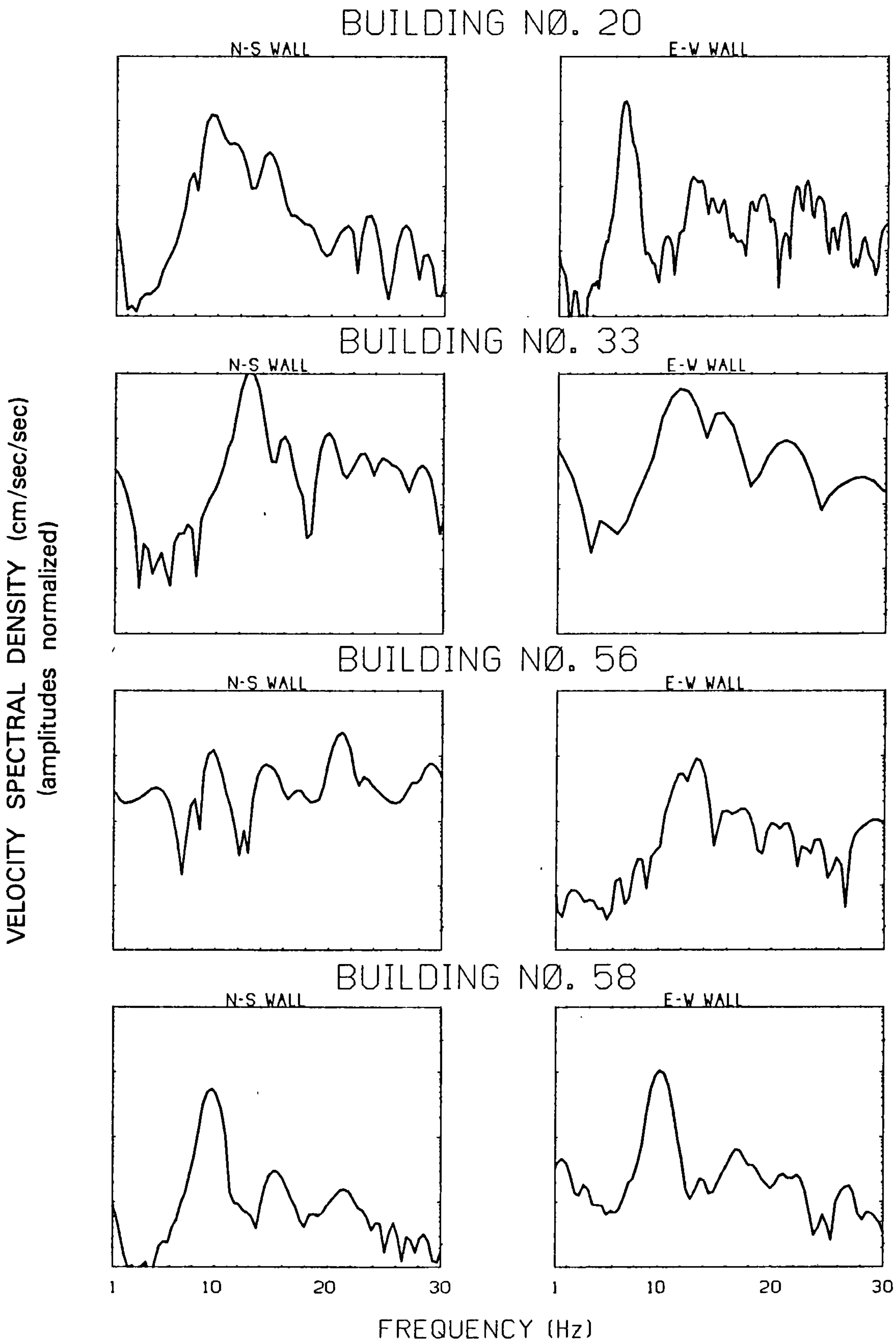

Figure 4.--Normalized spectra for north-south and east-west walls of 4 buildings. Spectra are derived from recordings of man-induced seismic energy applied directly on the walls.

Table 2.--Building vibration tests

Building No.	Bearing wall	Natural frequency (Hz)	Percent damping	Site response function
2	West	16.7	2.8	---
	North	5.7	3.2	
19	West	12.2	---	---
	South	11.0	1.6	
20	West	10.0	1.9	---
	North	6.8	2.5	
	East	9.6	2.8	
	South	10.9	1.6	
33	West	12.8	4.1	---
	East	12.9	3.0	
	South	12.2	3.7	
36	East	15.5	3.9	---
	South	14.0	5.6	
37	North	6.4	5.6	---
	East	11.3	4.5	
38	West	8.0	5.6	---
	North	5.3	4.1	
51	East	10.2	1.8	---
	South	10.5	4.8	
51A	West	9.2	6.9	---
	South	5.3	---	
56	North	13.4	1.8	---
	East	9.7	2.4	
58	North	10.1	2.9	---
	East	9.7	3.9	
95	North	12.5	3.1	2.5
	East	11.2	2.9	
96	West	9.8	3.2	3.1
	North	9.8	3.8	
130	East	9.4	2.4	2.5
	South	11.3	1.9	
164	East	3.7-9.8	5.8	2.9

Table 2--(Continued)

Building No.	Bearing wall	Natural frequency (Hz)	Percent damping	Site response function
165	West	8.2	7.8	2.0
	North	10.6	6.9	
165A	West	11.3	7.0	---
	South	8.2	7.0	2.0
167	North	12.6	3.4	---
	East	9.0	2.7	
	South	10.3	3.7	
168	North	18.1	1.6	---
	East	9.6	2.9	
	South	17.2	2.4	
179	West	9.5	---	---
	North	10.6	---	
184	East	10.2	3.4	---

area, they are probably underlain by unconsolidated sediments that are greater than 15 ft thick and higher in clay-silt content (greater than 60 percent) than the sediments underlying Paguate. The building-damage that was sustained in Paguate and the two comparison villages is shown in table 3.

Table 3.--Village building-damage comparison

Scale	Paguate %	San Felipe and Santo Domingo %
1	0	10
2	30	62
3	48	22
4	18	4
5	3	2

Test Borings and Pits

Forty test borings were completed within the village of Paguate together with 25 shallow refraction surveys (fig. 5). The data from the borings and the refraction lines were used to map the thickness of the low-seismic-velocity material underlying the village. Ten core samples 2-5 in. (5-10 cm) in length were recovered from the boreholes. The core samples were analyzed for grain size, sand/clay ratios, void percentages, and any evidence of a perched or changed water table (staining, water content, and so forth) (table 4). The percentage of the core that was recovered was documented. The amount of core that was lost due to compaction and the void ratios give an indication of the differential-compaction potential. Sections of the foundations under a damaged bearing wall were exhumed and inspected for evidence of distortion and (or) displacement.

Of the test borings, thirty were made to measure the thickness of sediments and soils over the bedrock underlying the village. The data from the borings along with the refraction-survey results show that the thickness of the unconsolidated sediments and (or) materials with a propagation velocity of less than 3,500 ft/s (1,066 m/s) overlying the sandstone bedrock varied from less than 1 ft (.3 m) in the general area of building 6 to more than 15 ft (4.6 m) in the areas of buildings 164, 206, and 220 (fig. 6). The thickness of low-propagation-velocity material exceeds 15 ft (4.6 m) in the area of "China Town" and in the area west of the village in the drainage valley. Test cores were made to a 24-in. (.6-m) depth near buildings 16, 20, 21, 82, 93, 165, 167, 184, and 308. The coring was inconclusive at buildings 20, 21, and 184 as bedrock was less than 24 inches deep. The compaction of the cores recovered at the remaining sites was less than 5 percent which gives a general indication of the sediments' low compaction susceptibility.

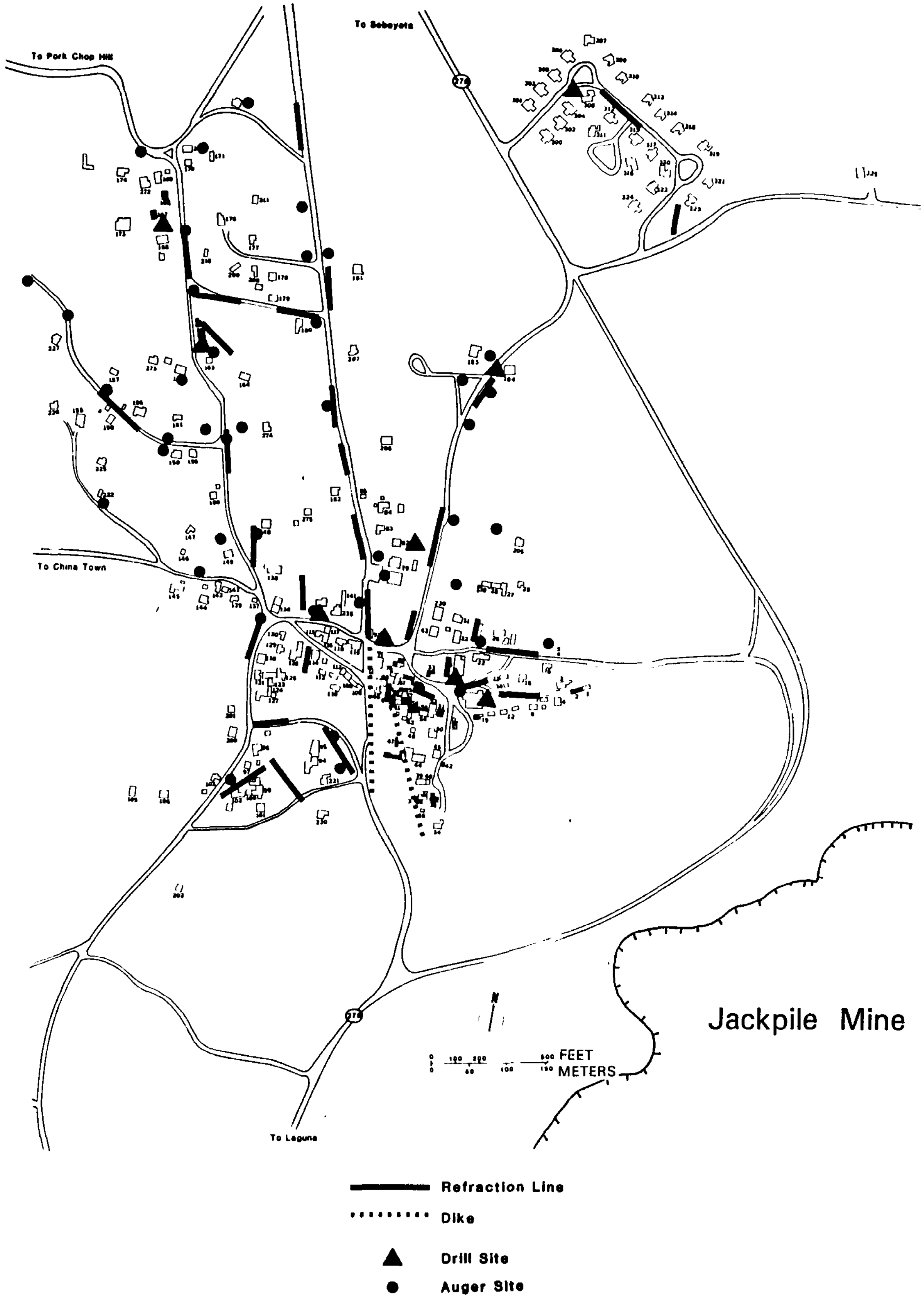

Figure 5.--Seismic study in the Paguate area showing drill and and auger test locations, lines of refraction, and alignment of exposed rock dikes.

Table 4.--Soil sample test results

Site No.	Average depth	Sand 4.76-0.075 (mm)	Silt 0.075-0.005 (mm)	Clay 0.005 (mm)	Stain	Percent recovered	Grain density (gm/cc)
16	10 cm	65.88	20.22	13.87	Brown	100	2.71
20	<10 cm	Rock	---	---	---		
21	<10 cm	Rock	---	---	---		
82	10 cm	67.81	22.42	9.74	Brown	98	2.77
93	10 cm	58.43	30.43	11.13	Brown	95	2.84
165	10 cm	44.06	36.14	19.80	Brown	96	2.74
167	10 cm	52.12	35.46	12.42	Brown	95	2.73
184	<10 cm	Rock	---	---	---		
308	10 cm	55.34	37.45	7.21	Brown	95	2.76
165	1 m	43.87	44.05	12.08	Yellow	100	2.78
167	1 m	50.32	35.52	14.16	Yellow	98	2.84
165	2 m	61.26	23.66	15.08	Yellow	98	2.88
167	2 m	48.58	41.77	9.65	Yellow	96	2.85

A mean void ratio was computed for the samples from sites 165 and 167 by the relation VR = (GS/GD)-1 where VR is the void ratio, GS is the dry density and GS is the density of the material without the voids. Core samples were also recovered at 4-ft (1.2-m) and 6-ft (1.8-m) depths at buildings 165 and 167. The mean void ratios at the sites tested varied between 0.55 and 0.65. The highest void ratio calculated was 0.65 at a 24-in. (.6-m) depth at building 16. No hydrological data or obvious water-induced staining or precipitation, indicative of a changed water table, was detected in the core samples or bore holes.

Test pits were located beneath large cracks in the walls of the buildings. Two- to three-foot (.6- to .9-m) sections of the foundations supporting bearing walls were exhumed at buildings 34 (one wall), 36 (one wall), 165 (two walls), 167 (two walls), 179 (two walls), 202 (two walls) and 220 (two walls). All buildings except 34 and 36 had at least 18 in. (.45 m) of footing material (rock and (or) concrete) under the walls; the foundations of buildings 34 and 36 are located on sandstone bedrock. The inspections of the foundations indicated no discernible displacements. The cracks in the walls were not observed to continue through the foundations exposed in the test pits at buildings 165, 167, 179, and 220. The foundation inspection at building 202 was inconclusive as displacements and (or) cracks could have been present in the foundation here, but due to the friable nature of the soil in the test pit, the foundation could not be seen in a undisturbed condition.

TEST EXPLOSIONS

Induced ground motions from eight test explosions were recorded at pertinent sites in the village. Each test explosion consisted of 100 lbs (45.4 kg) of ammonium nitrate/fuel oil mixture in a borehole that was 60 ft (18.3 cm) deep and 6 in. (15.2 cm) in diameter. The explosive mixtures were tamped with soil to the surface and all blasts were contained. Seven explosions were located east of the village and one event was south of the village, on Laguna Reservation property near the west wall of the Jackpile quarry (fig. 7). The tests were a part of the investigation that was designed to compare the peak particle-velocity ground motion and velocity spectra at several pertinent sites in the village. The rate at which ground motion decreases with distance from the source (attenuation), the way that individual sites respond to the induced ground motions (site response), and the response of selected buildings to the ground motions (building response) were analyzed using the seismic data from the test explosions. Five portable engineering seismograph systems, each with three orthogonal, velocity-sensing seismometers were used to record the ground-motion data from each test explosion.

Ground-motion attenuation with distance from the explosion was calculated using data obtained from sites underlain by bedrock (to minimize the site-response effects) and at similar bearings but in different distance ranges from the source (from 2,150 to 5,240 ft; 655 to 1,047 m). Analysis of the seismic data induced from the explosions (figs. 8 and 9) yielded the peak-particle-velocity-ground-motion-attenuation and velocity-spectral-ground motion-attenuation values throughout the village. Using least squares regresion, the attenuation data was fit to the equation A = cR, where A is the amplitude in cm/s (velocity of peak particle ground motion) or cm/s/s (spectral velocity density), c is a constant, and R is the explosion-to-site distance. The relationship obtained is $A = cR^{-1.87}$ for peak particle,

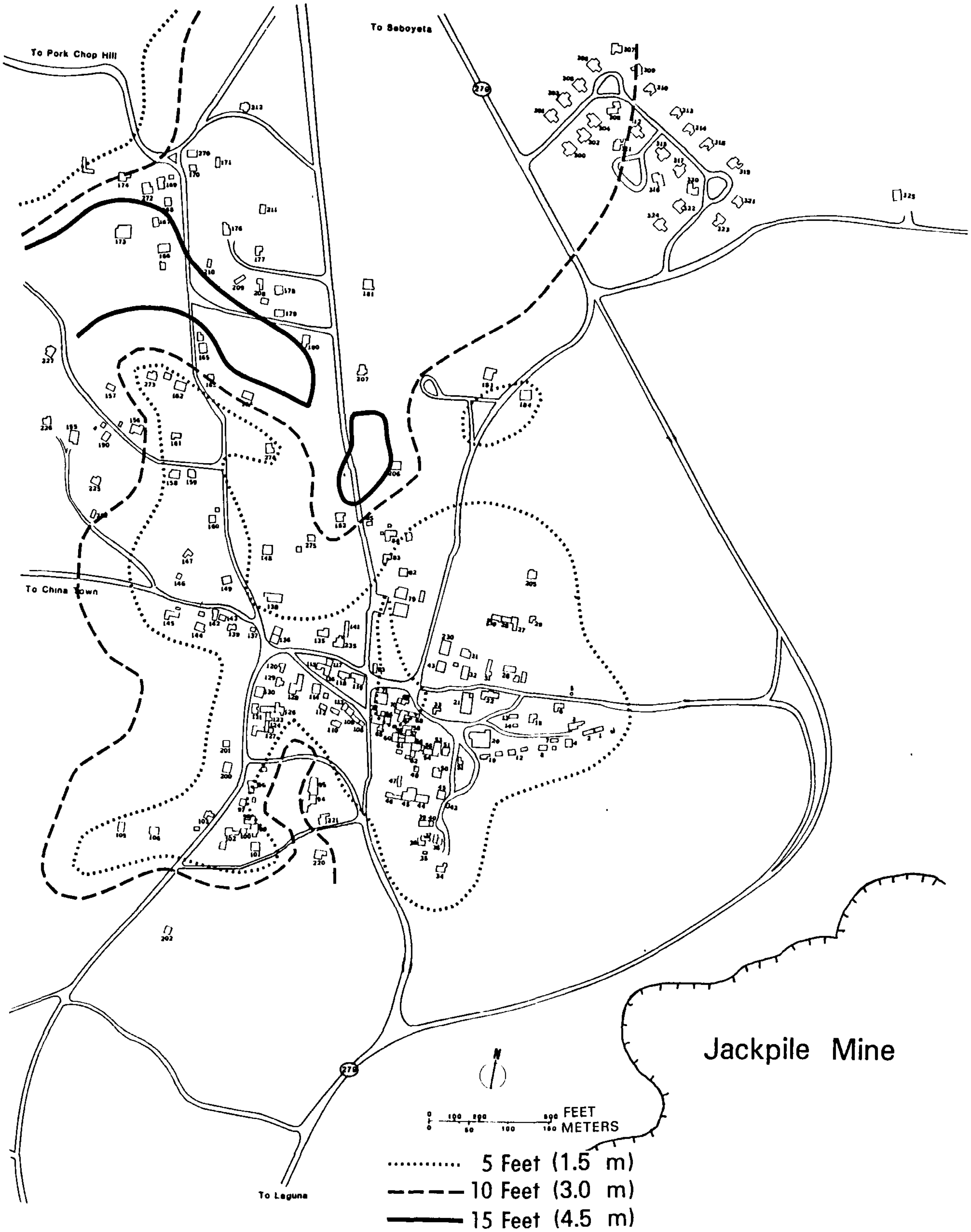

Figure 6.--Contour lines showing the thickness of low-velocity (seismic propagation velocity) materials as measured by seismic-refraction methods and auger holes. Low velocities are those less than 3500 ft/s (1066 m/s).

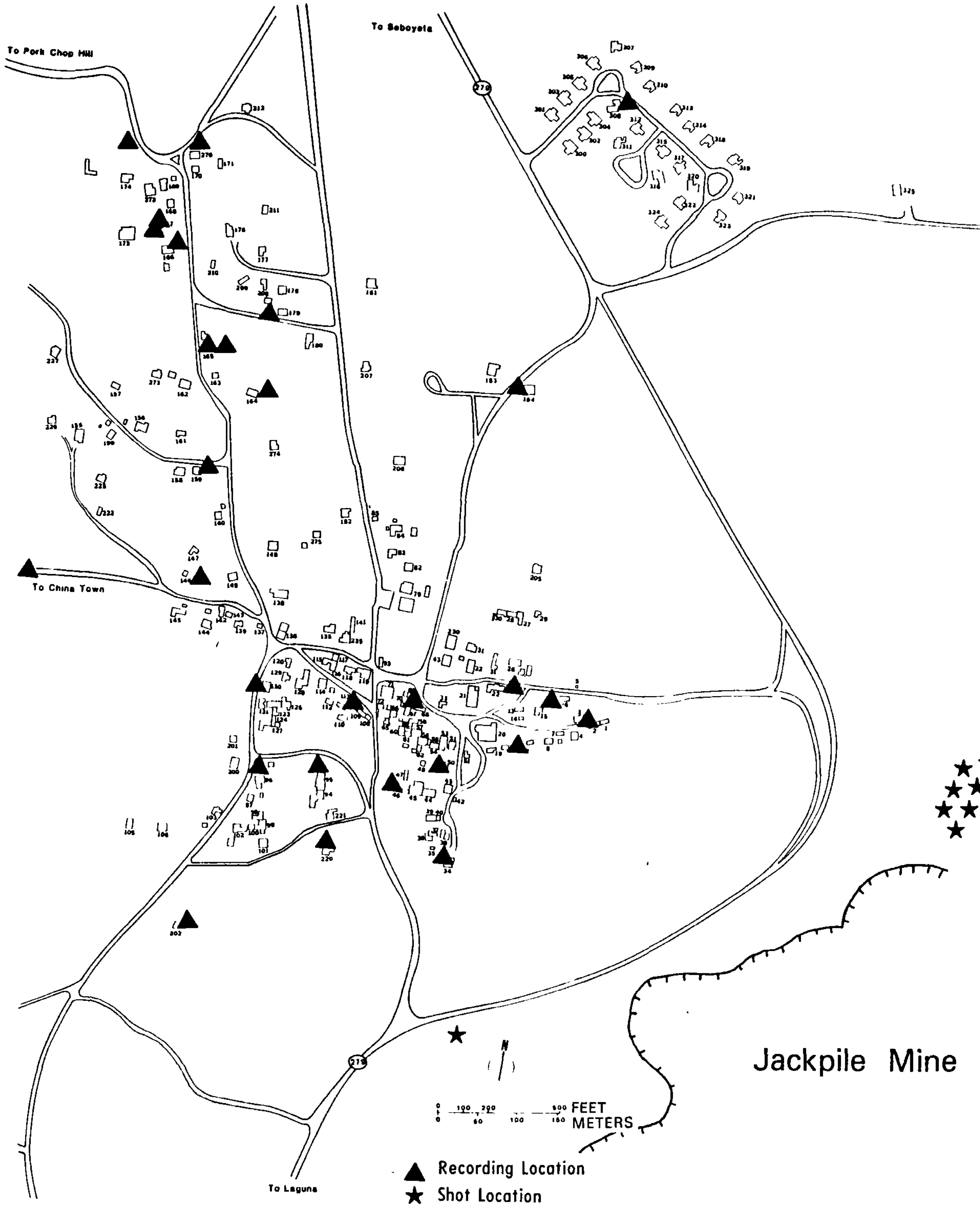

Figure 7.--Seismic study in the Paguate area showing shot and recorder locations.

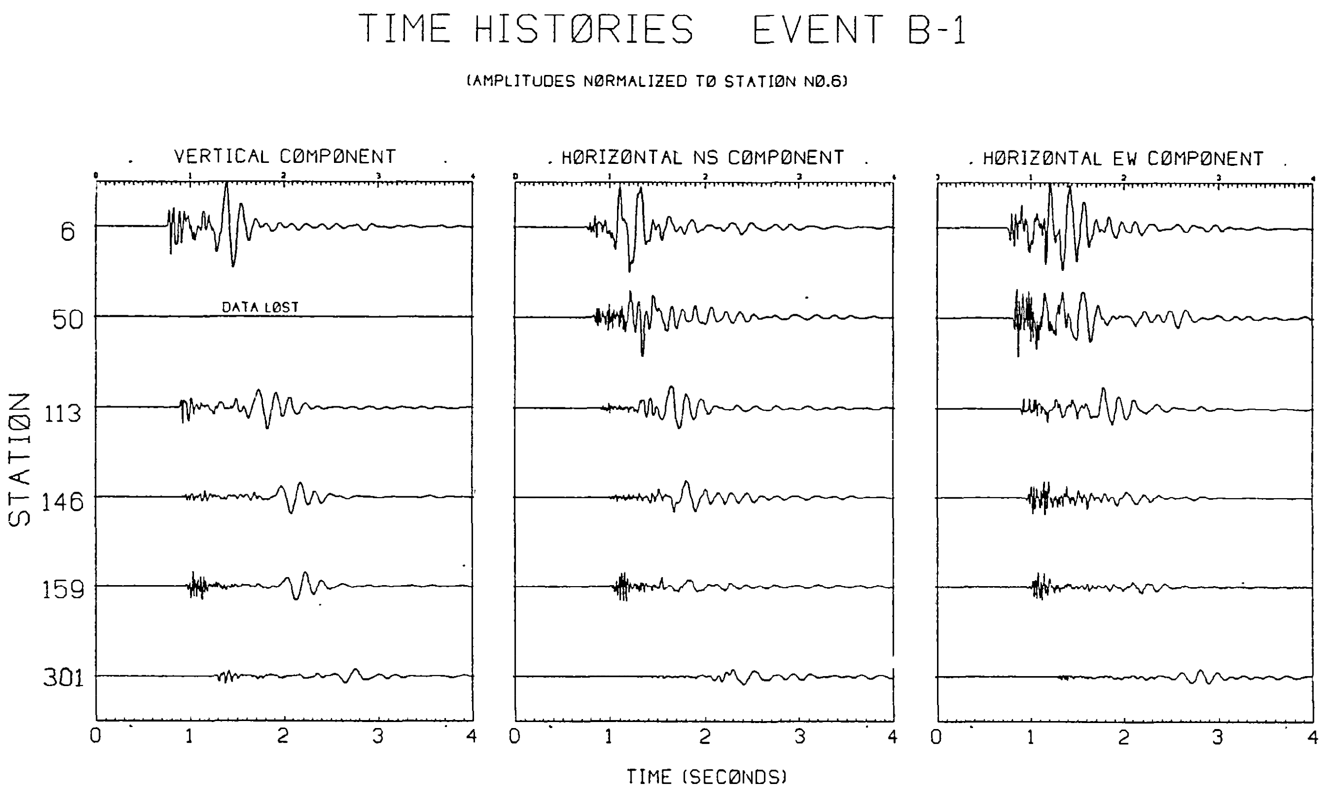

Figure 8.--Three-component time histories of the test explosions recorded at 6 buildings in the village of Paguate.

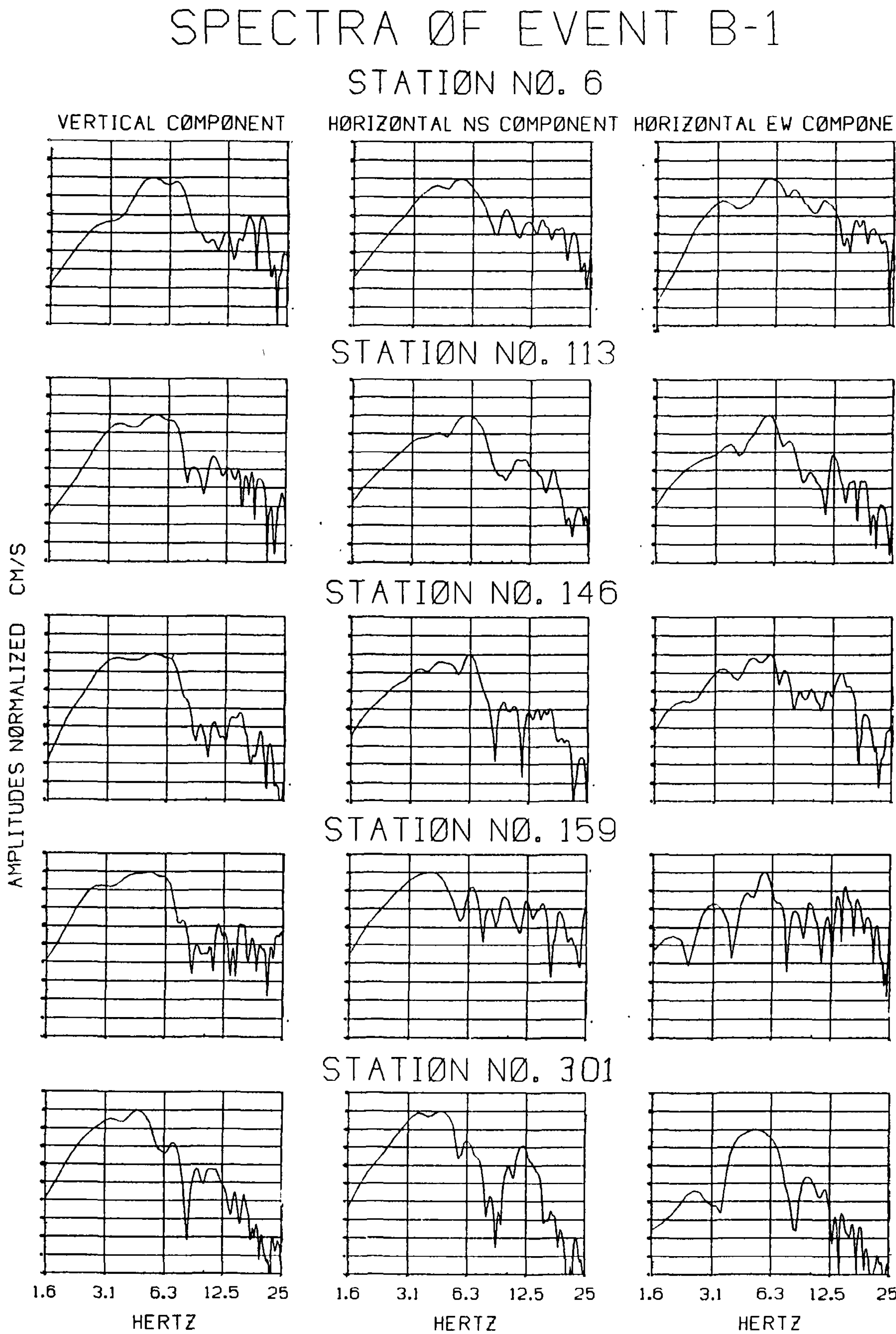

Figure 9.--Spectra generated from time history recordings of test explosions.

vertical ground-motion velocity and $A = cR^{-1.15}$ for peak particle, horizontal ground-motion velocity. The ground-motion, spectral-velocity, attenuation-scaling functions are similar to the peak particle scaling function except that spectral attenuation is scaled for a range of frequencies between 1 and 15 Hz (fig. 10).

Portable engineering seismograph systems were operated near building 146 and (or) building 6 during each test explosion. The recordings at these sites were used as the standards for comparison with the recordings from all other sites. Site 146 was used as a reference because it is underlain by bedrock (sandstone) not by unconsolidated sediments or soil which can affect or modify the explosion-induced ground motions. The site response on competent bedrock is assigned a ground-motion amplification factor of 1 which reflects the assumption that the site does not amplify the induced ground motion from the source. Site 146 is at a similar range from the test explosions as several buildings that have a damage-scale degree of 4 to 5. Site 6 was used as a reference because the site is located nearer the test explosions than most of the buildings in the village and because the building at this site has a damage-scale degree of 2.

The normalized velocity spectra derived from the ground motions recorded at sites 6 and 146 from the test explosions east of the village are also used to calibrate the variations of the input sources. The highest and lowest spectral values at these sites are shown on figure 11A. The comparisons indicate that the data from the eastern test explosions are, in general, comparable from one event to another because the test explosions were of the same approximate size, distance, and bearing from the recording sites. A similar comparison is made for sites 6 and 68 (fig. 11B) to document the variations of the input sources located east of the village versus the input sources located south of the village. The ground-motion variation due to the difference in the bearings of the test explosions shown on figure 11B is larger than that on figure 11A due to the larger difference in the distances from the events; however, the general spectral shape is similar.

The spectral ratios between the standard rock site (146) and site 164 (damage rating of 4) show that there is a site amplification of the horizontal ground motion at site 164 in the frequency band of 3.8-10.1 Hz. The peak site amplification of the east-west horizontal component of ground motion at this site is 5.1 at 6.2 and 8.9 Hz. The peak site amplification in the north-south horizontal component is 2.9 at 10.9 Hz (fig. 12). Site 165 (damage rating 5) which is 350 ft (107 m) farther from the source than the rock site (146) also shows a site amplification. The site amplification of the horizontal ground motions at site 165 peaks at a factor of 8.2 at 6.4 Hz in the east-west component and a factor of 3.1 at 13.2 Hz in the north-south component (fig. 13).

The recorded ground motions from the sites in the village were compared to the seismic data recorded at the standard rock site (146) and (or) the close-in low-damage site (6). The comparisons are made by taking the ratio of the spectra at any site to that at the standard sites (146 or 6) The spectral ratios (SR) are calculated by: $SRf = SCf/SSf$, where f = frequency in Hz, SS = standard site spectra (146 or 6), SC = site being compared. The spectral amplitudes and the site transfer functions show the frequencies that are amplified at that particular site. The site transfer functions to the close-

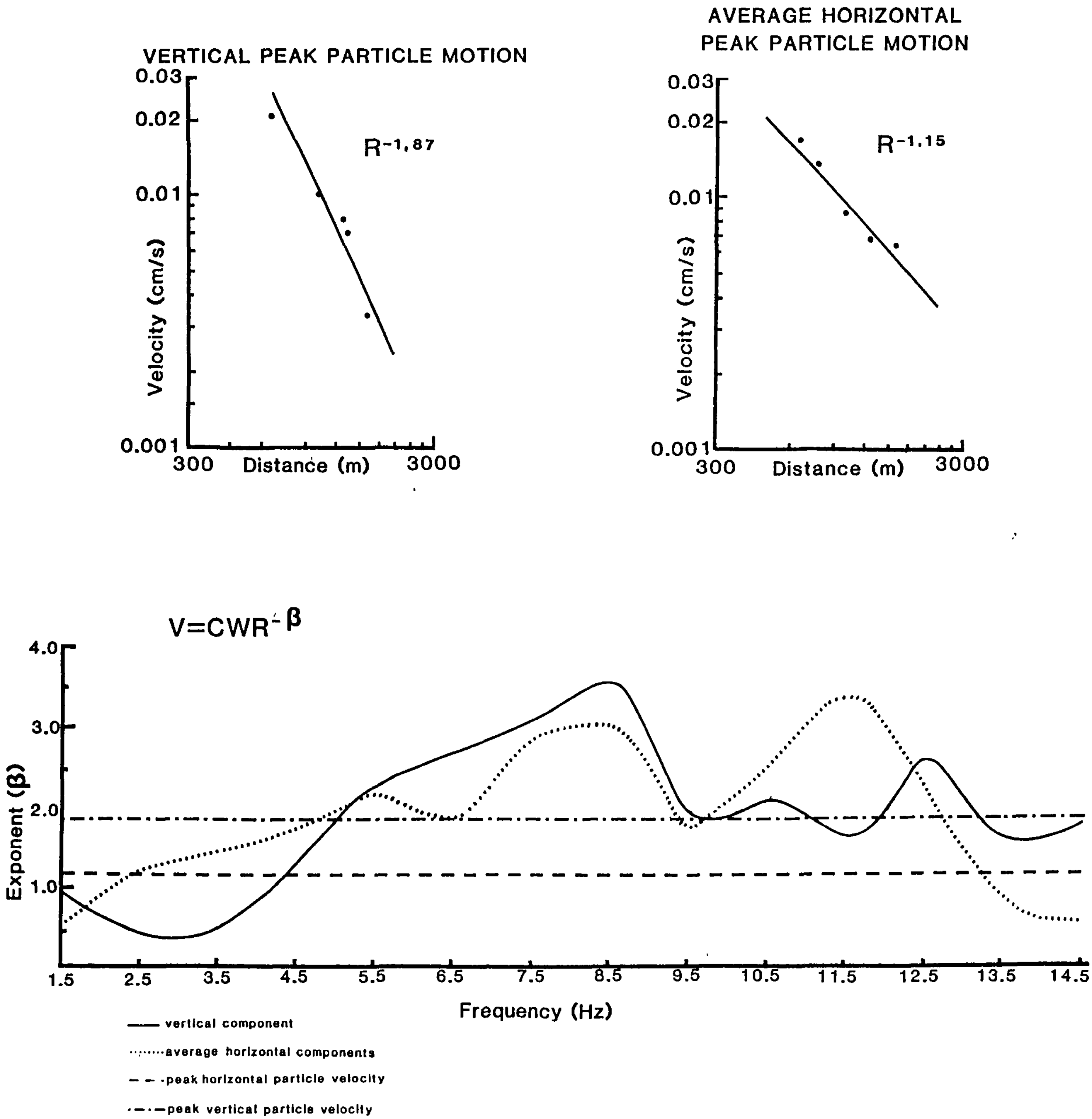

Figure 10.--Upper two graphs show the attenuation data. Bottom graph shows the attenuation for the vertical and average horizontal components where V = ground motion in cm/s; C = constant; W = yield in pounds; R = distance from the event in meters; B = slope of regression line.

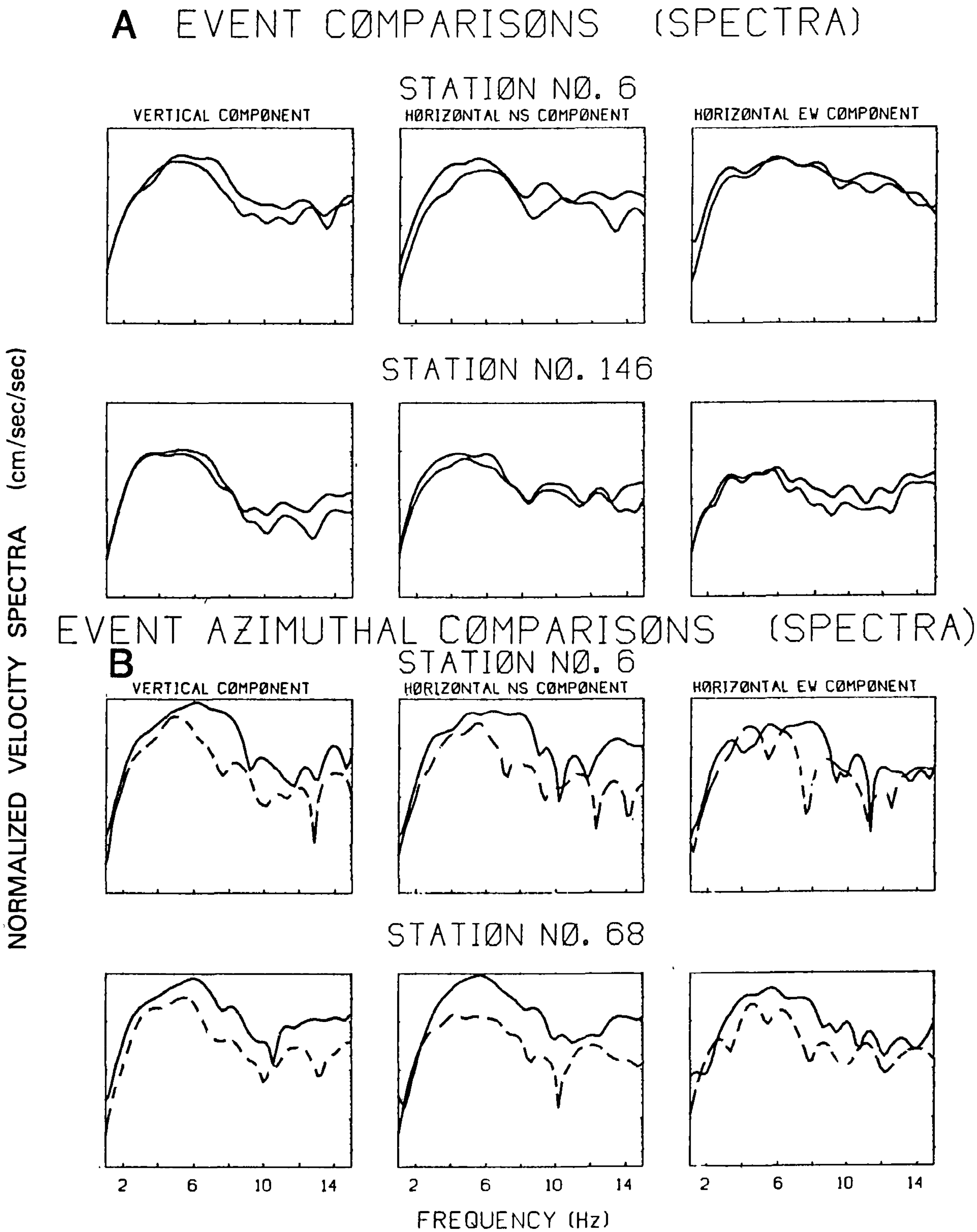

Figure 11.-- **A**, Test-explosion velocity variations are small as shown by the small variation in the ground-motion spectra. The highest and lowest spectral values recorded at sites 6 and 146 are shown. **B**, The variation in spectral values obtained from explosions east of the village (solid lines) is compared to the one south of the village (dashed lines).

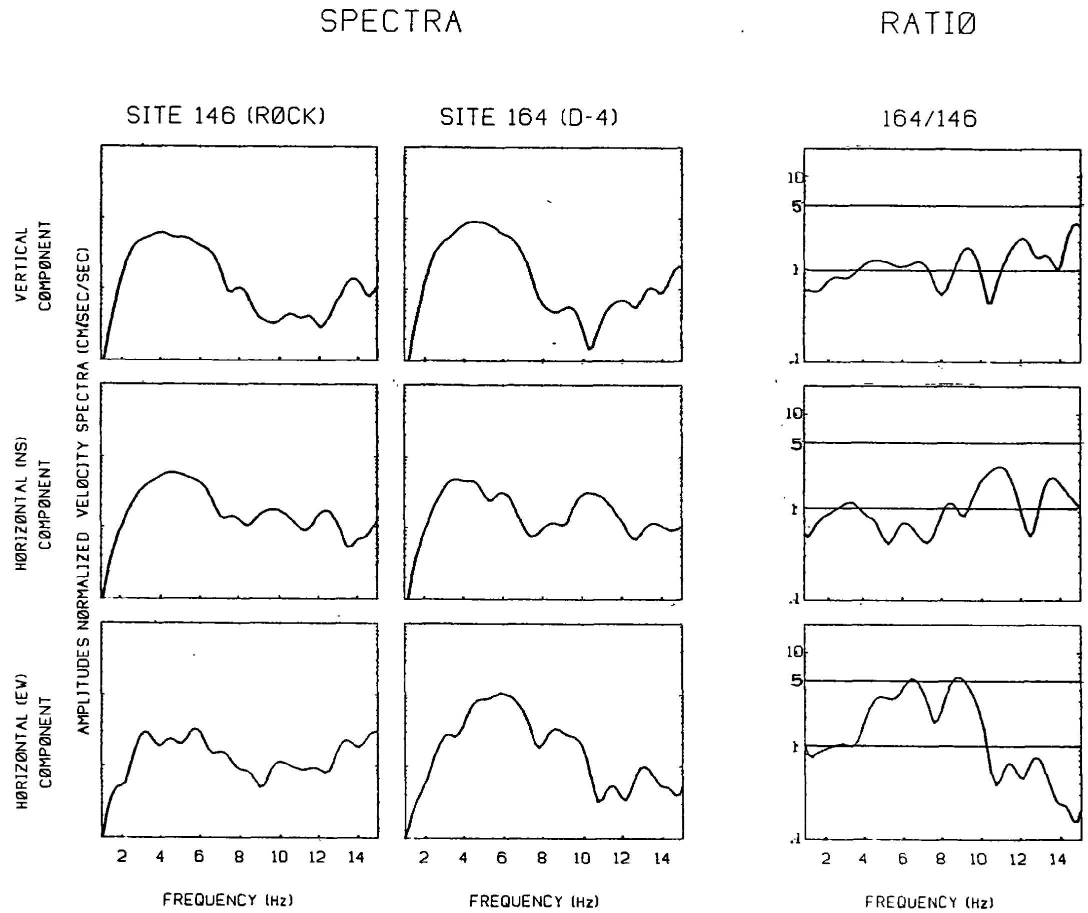

Figure 12.—The velocity spectra of three components of ground motion and their accompanying ratios (sites 146 and 164) show amplification of ground motion at site 164, especially in the east-west horizontal component.

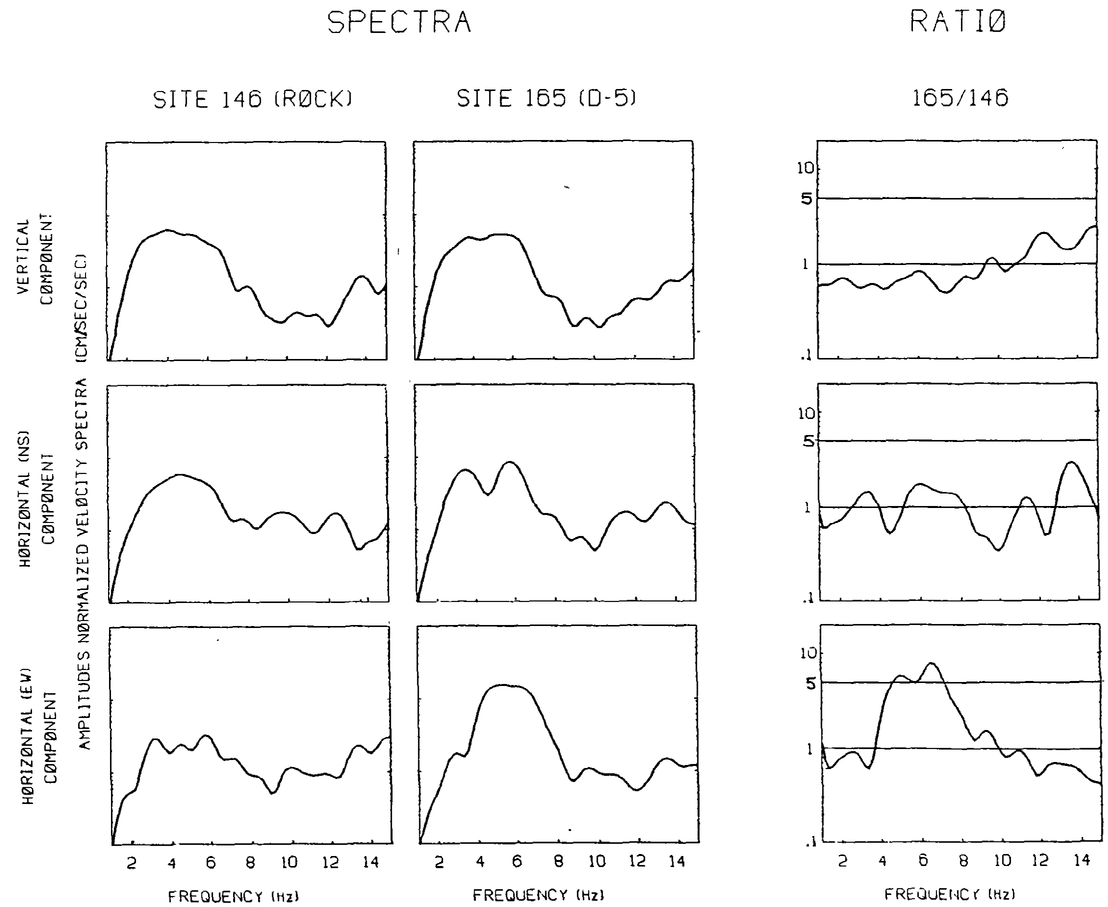

Figure 13.--The velocity spectra of three components of ground motion and their accompanying ratios (sites 146 and 165) show amplification of ground motion at site 165, especially in the east-west horizontal component.

in low-damage site shows the frequencies at which amplification occurred at various distances from the explosions. Analysis of the test-explosion data from the village sites, compared with data from the standard rock site (146) and the low-damage site (6), shows that most of the sites investigated have ground-motion amplification due to site response and that the amplification is frequency dependent. Amplification of ground motion associated with the geotechnical properties of underlying soils has been documented as a phenomonon by a number of authors (Gutenberg, 1957; Kanai, 1952; Borcherdt, 1970; Hays, Algermissen, and others, 1978; Rogers and others, 1979; and King and others, 1983, 1986).

Figure 14 shows the comparisons (ratios) of the spectra between the rock site (146) and several other sites in the village. The ground motion on bedrock can be predicted for the sites in the village and (or) factored to the bedrock station based on the attenuation functions calculated in the previous section. The seismic data from several sites in the village were normalized by using the average attenuation functions with the following equations: $Ac/As = (Rc/Rs)^{-1.87}$ for the vertical component and $Ac/As = (Rc/Rs)^{-1.15}$ for the horizontal component, where Ac is the velocity value at the site being compared, As is the velocity value at the site that is being compared to (rock site or low-damage site), Rc is the distance from the source of the site being compared, and Rs is the distance of the standard site from the source. Solving the equation to normalize the ground motions at sites 130, 96, and 95 to the rock site yields factors (Ac/As) of 1.4, 1.4, and 1.6 for the vertical component and 1.2, 1.2, and 1.4 for the horizontal component of ground motion (factors are greater than the ground motion at the rock site as the sites are 500, 600, and 800 ft (152, 183, and 244 m) closer, respectively, to the source than the standard rock site). The actual factors (AF) from the recorded data, derived by dividing the rock-site velocity spectra into the comparison-sites velocity spectra, are 4.3, 4.9, and 9.2 for the vertical component and 4.1, 6.1, and 5.0 for the horizontal component, respectively. The approximate site response at these three sites can be closely estimated by the general formula: $Af - Nf = SR$, where Af is the rock-to-site factor from recorded data, Nf is the derived rock-to-site factor from the attenuation or predicted site ground motion, and SR is the site response at that particular site. The site responses for these three sites are approximately 3, 5, and 4 in the horizontal component, respectively. Site 166, which is approximately 400 ft (122 m) farther from the test explosion than the standard rock site, has a scaled ground-motion factor of 0.8 to the standard rock site in the vertical component and a factor of 0.9 in the horizontal component as compared to the actual recorded ground-motion factors (AF) of 5 in the vertical component and 11.1 in the horizontal component. The addition of these factors will give a peak site response at site 166 of 6 in the vertical component and 12 in the horizontal component.

A comparison of spectral ratios was made among the seismic recording sites in the village and a low-damage (site 6; damage scale 2) site that is closer to the source (2,150 ft; 655.3 m) than the other sites investigated. Spectral ratios at all sites compared show equal or higher ground motions at selected frequencies in the 1-15 Hz band than were recorded at the low-damage site (6) (figs. 15 and 16). The comparisons also show that the site response amplifications of the ground motions are frequency dependent; that is, selected frequencies show increased ground amplification factors compared with the close-in site. For example: site 34 shows an amplification factor of 5.9

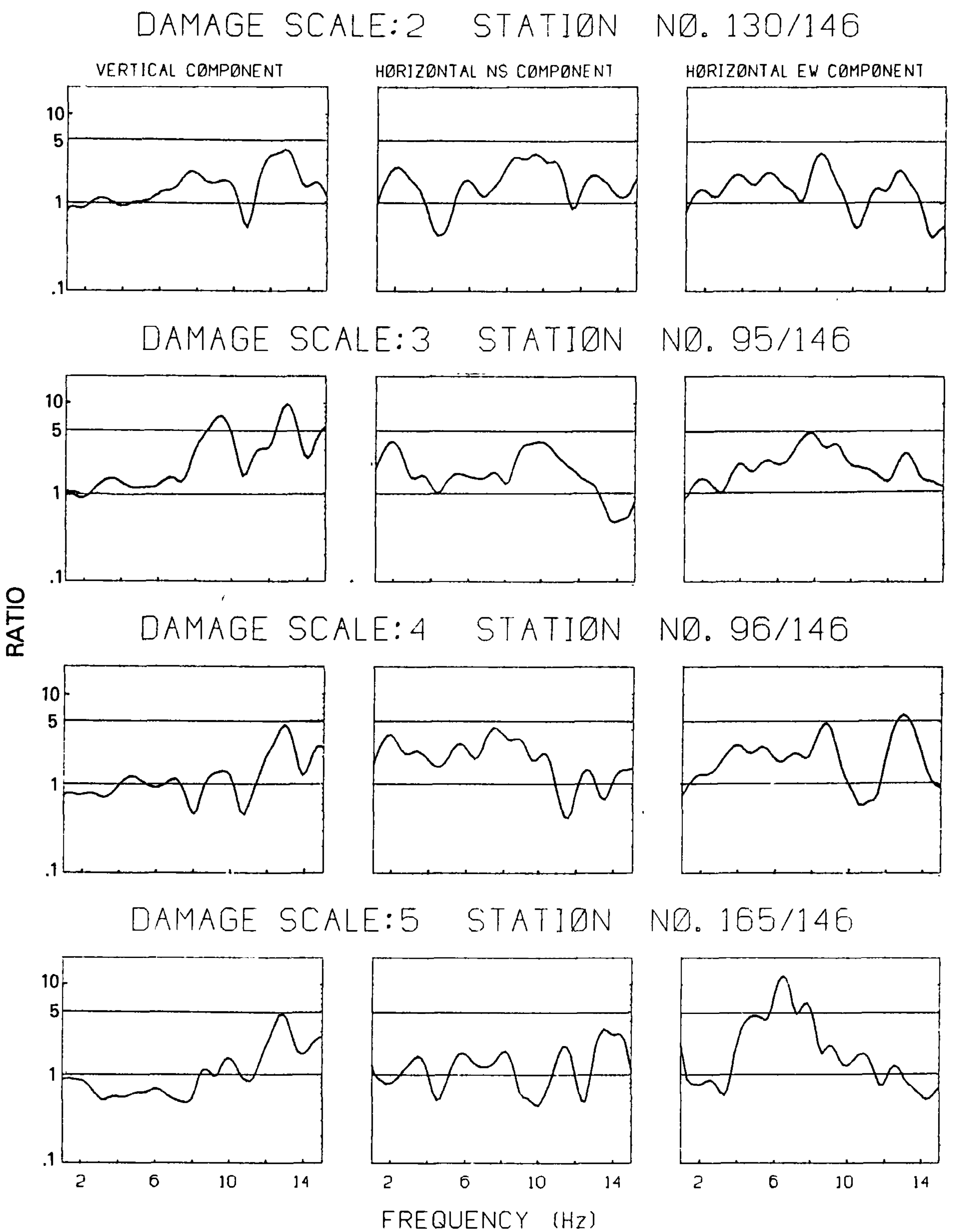

Figure 14.--Comparisons (ratios) of the velocity spectra between the rock site (146) and several other sites in the village. The damage scale rating is also indicated for that site.

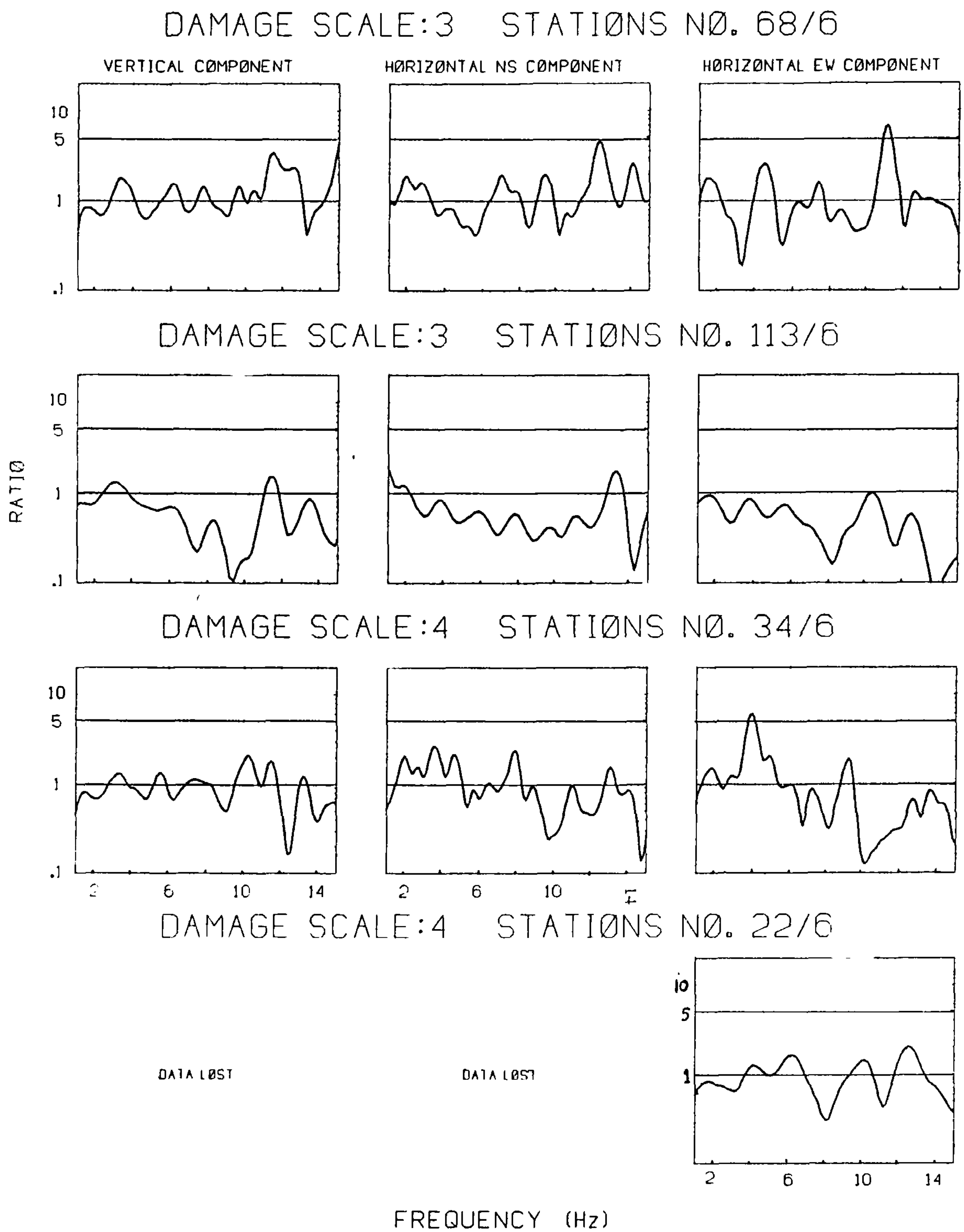

Figure 15.--Comparison of the spectral ratios for all three components between several sites and site 6 - a low-damage site (scale 2)- which is closer to the test explosions than the sites to which it is compared. The ratios show equal or higher ground motion at selected frequencies in the 1-15 Hz band than were recorded at site 6.

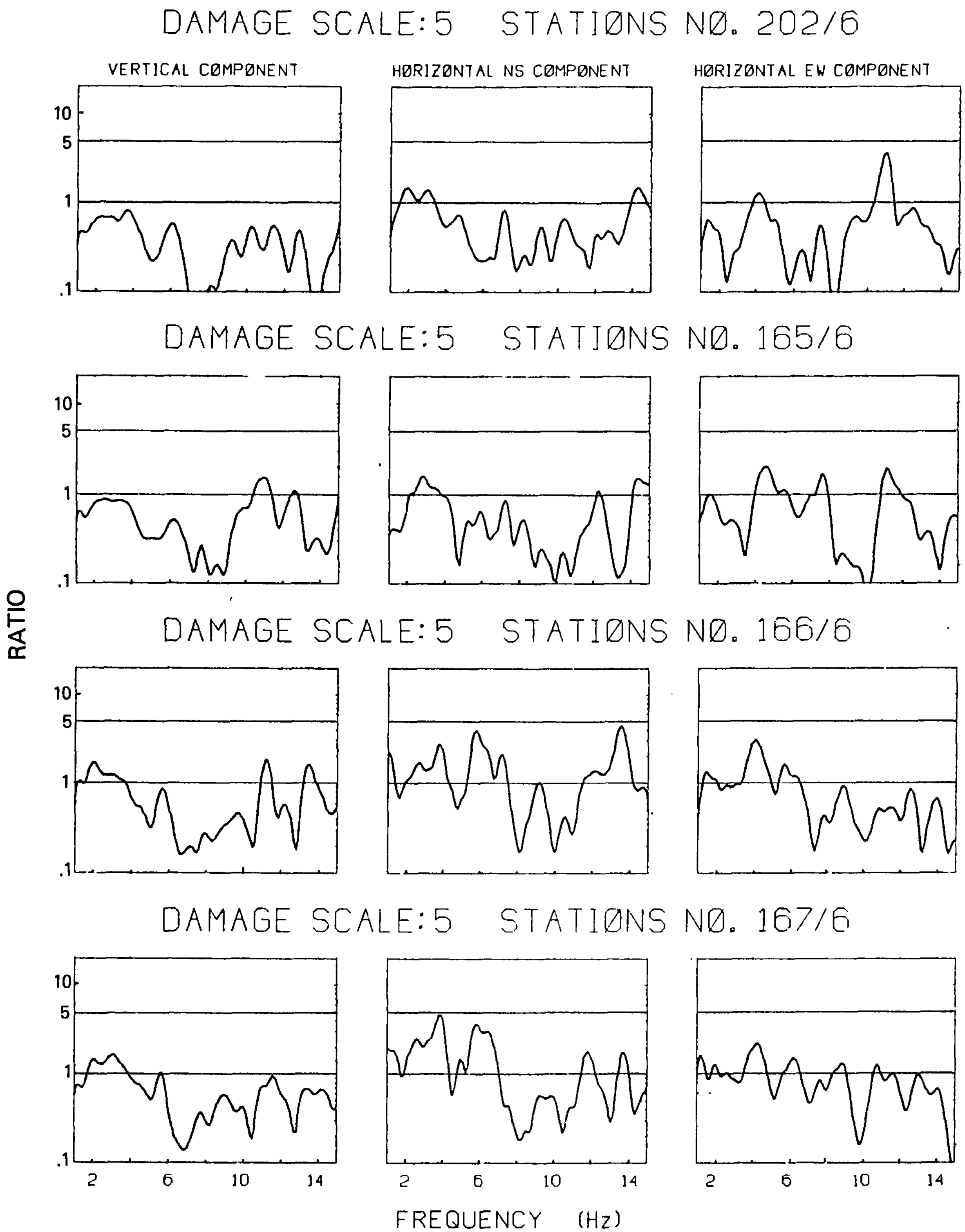

Figure 16.--Spectral ratio comparison for all three components between site 6 and several sites with a damage scale rating of 5.

at 3.8-4.1 Hz in the east-west horizontal component, whereas the factor would be 0.8 if based only on the attenuation function. The 1.6 amplification at 12.5 Hz is a more critical factor since the natural frequency of the building at that site is approximately 12.2 Hz (table 2). A direct comparison of the ratio factors and the predicted numbers based on the attenuation functions are shown in table 5.

Table 5.--Predicted versus actual peak ground motion

Site No.	Predicted V factor	Actual factor	Peak Hz	Predicted H factor	Actual factor	Peak Hz
68	.89	3.6	8.2	.93	7.2	9.3
113	.51	1.6	11.0	.66	2.1	12.4
34	.69	2.1	9.8	.80	5.9	3.5
22	.78	---	---	.86	2.1	12.2
202	.88	.86	3.0	.89	3.8	10.5
165	.25	1.8	10.6	.43	2.0	4.2
166	.22	2.0	11.0	.39	4.9	13.5
167	.22	1.4	3.2	.39	4.9	3.6

The structural-response data of two buildings (165 and 167) were obtained by installing a portable seismograph system on the tops of bearing walls of the buildings with another seismograph system located approximately one building height from the base of the buildings. The systems then recorded both the ground and structural motions caused by the induced ground motions from one of the test explosion events. The test was made to obtain the structure-transfer function of the bearing walls of the buildings. The transfer functions or spectral ratios of the buildings were calculated in a similar manner to the transfer function for the various site conditions (top-of-bearing-wall spectra/ground spectra). The ground-motion frequencies that are amplified by the structural response depend on the natural frequencies of the structure and the coupling of the building to the ground (Tschebotarioff, 1951). The spectral ratios of the induced motions show that building 165 will amplify most input frequencies between approximately 6 and 14 Hz with peak amplification factors of 5.1 at 11 Hz in the north-south horizontal component and 3.2 at 9.2 Hz in the east-west horizontal component. Building 167 will amplify frequencies from approximately 6 to 11 Hz in the east-west horizontal component with a peak amplification factor of 6.5 for the frequencies from 9 to 11 Hz in the east-west horizontal component (fig. 17).

DISCUSSION

The damage survey in the village of Paguate shows an overall intensity pattern that is irregular in areal distribution and not related to distance from the Jackpile open-pit mine. The most heavily damaged structures are generally in clusters of buildings which are located farther from the mine than are lesser-damaged structures. The parameters that might primarily contribute to or be the cause of the observed damage to the buildings in the village are thermal and moisture-activated expansion and contraction of building materials, construction methods (for example, poorly constructed

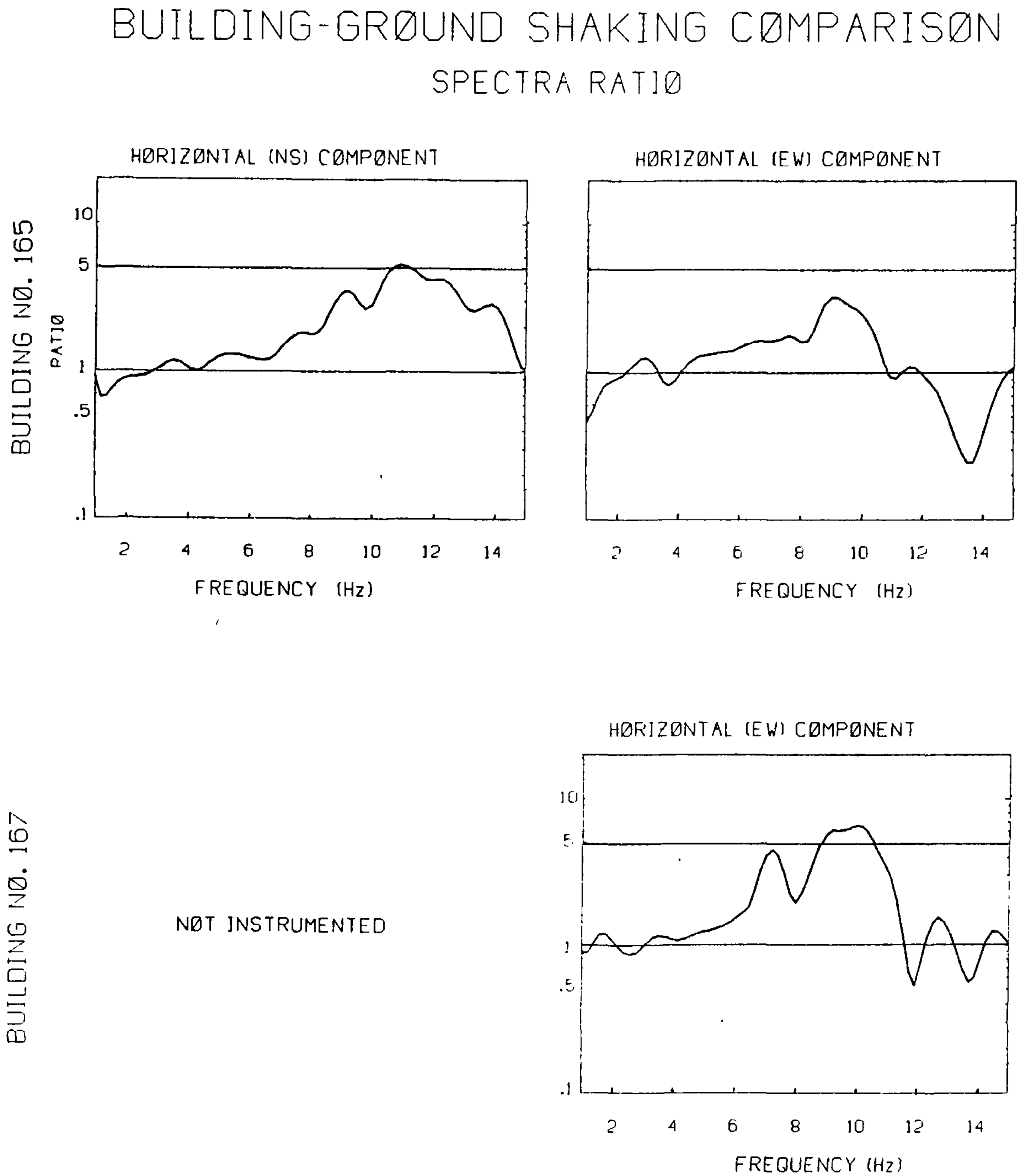

Figure 17.--The spectra for sites 165 and 167 were compared with the ground-motion spectra measured one building height from the base of the building. Ratios show the frequencies that are amplified by the structural response of the building.

lintels, vigas, bond beams, and so forth), differential compaction under the foundations, and (or) vibration damage.

Cracks in a mud- or adobe-veneer-over-rock ("Chaco") type building due to shrinking or drying of material will generally form a partial or complete polygonal pattern, will generally be small in width due to the limited volume contraction of the material, and will not continue through a second medium (rock or wood). Poor design and (or) construction of the type of buildings found in Paguate will usually result in damage occurring damage near the soil/building-base interface (due to a poor foundation and (or) capillary action of moisture into the adobe), will show a separation of the bearing walls (due to poor bond beams) with the largest separation near the top and diminishing toward the bottom, and similar obvious construction flaws. If shrinkage and construction damage could be specifically identified, it was not considered as a contributary cause. The buildings that were surveyed for degree of damage in the other two villages were similar in construction and materials; therefore, the differences in the damage pattern in Paguate compared to the villages of San Felipe and Santo Domingo are probably due to differential compaction beneath the building foundations and (or) vibration damage from ground motion.

The majority of the buildings in the most densely concentrated groups of buildings in Paguate (south-central and northwest areas) have foundations that either rest directly on bedrock or are underlain by 1-2 ft (<1 m) of compacted sand/clay soil on top of bedrock. Differential compaction could not be a factor in the damage to these buildings. Other buildings in the northwest area are underlain by approximately 5-8 ft (1.5-2.5 m) of unconsolidated sediments that overlie 5-8 ft (1.5-2.5 m) of low-wave-velocity bedrock (weathered sandstone). The void ratios, the sand/clay mix, evidence from exumed foundations, and damage cracks that do not extend into the foundations all suggest that differential compaction is not the cause of the observable damage.

Differential compaction can not be discounted as a contributing damage factor, however, for the buildings located on the deeper sediments in the southwest area of the village where lowering of the water table could cause a change in the pore pressure of underlying sediments and thereby contribute to an increase or decrease of differential compaction under the foundations of a few of the buildings. Data from borings and refraction surveys in the southwest area, however, did not reveal any present or historical changes in the water table. Observable evidence of compaction, such as depressions, sinkholes, or sag areas, is not present in this area, which indicates that the forcing mechanism for the compaction would depend on the weight distribution of the buildings. The weight per area is relatively small due to the thick bearing walls and the small size of the buildings. which are all one-story, "Chaco", frame-mixed type structures with rock footings.

The site- and building-response studies clearly show that ground motions at selected frequencies in the 1-15 Hz frequency band are larger in areas underlain by thick layers of unconsolidated materials that are farther from the mine than in areas underlain by thin layers that are closer. The measured site response is shown by these studies to correlate well with the degree of building damage. An average site-amplification factor of 5 at frequencies between 1 and 15 Hz was calculated at sites underlain by unconsolidated sediments, and site 165 has a site-amplification factor of 11 at 6 Hz. These amplification factors indicate that the ground motions predicted by normal attenuation-scaling methods must be multiplied by factors of from 5 to 11 for selected frequencies. Comparison of the high-response areas with the standard sites (146 or 6) that was as much as to 2.2 times closer to the blast shows that the high-response areas farther from the blast receive as much or more blast-induced ground motion than the closer sites at selected frequencies. The data also show that the natural periods of the buildings coincide with the amplified site-response frequencies. The building-response study showed that on the two buildings tested, the building response amplified the natural frequencies of the buildings by factors of from 3.2 to 6.4.

The high mass, low structure stiffness, and high natural frequencies of the rock-adobe buildings in Paguate result in the buildings having a high susceptibility to damage from blast-induced ground motions. The general frequency band for induced ground motions from the test blasts is 1-15 Hz. The natural frequencies for the buildings range from 3 to 15 Hz with the mode concentrated at approximately 10-12 Hz. Additional construction and repairs made during the past 15 years do not seem to have retarded the damage to the buildings. Although the added stucco layers tend to cover the existing cracks in most cases, the cracks either can be followed through the rock core to the interior of the building or have reopened through the stucco.

The buttresses that have been added to buildings (such as at buildings 165 and 167) may slow differential compaction or support the weight of the walls which is what they are designed for in the "Spanish" type of adobe construction (O'Connor, 1973). The buttresses added to the buildings in Paguate have, in general, increased the buildings coupling to the ground and shortened the effective heights of the walls. The shorter walls have a higher natural frequency which is also in the bandwidth of the source. Therefore, the buttresses may have increased the sensitivity of the building to the ground motions in the frequency band most damaging to the buildings. Detuning or changing the natural frequency of the buildings away from the peak frequencies induced by the blasts would probably help miniminize the damage from the induced motions. In general, most of the repairs that can be observed did not either detune the buildings or strengthen the bearing walls.

The adobe and rock construction is less elastic than the average cement-block or stick-frame building. Once damaged or cracked, the adobe material used for surfacing the rock-core walls and the filler in the rock cores will not "heal" or return to its original state (Clifton, 1979). The cumulative effect of over 1,400 blasts which took place at the quarry could be significant; however, due to the lack of proper historic documentation and the limited scope of this investigation, the effects could not be evaluated.

The blast durations varied with the length of the row-type charges and the 0-9 ms shot delays the mining company used in their operations (U.S. Department of Interior, Bureau of Indian Affairs, 1984). Duration of ground shaking has been shown to be one of the more important parameters in the destructive capabilities of ground shaking (Hays, King, and Park, 1978). The data from the single test blasts show that the induced horizontal shaking at site 6 (low damage at 2,200-ft; 670-m range from the shot) and at site 165 (high damage at 4,400-ft; 1,341-m) range) will last approximately 1.5 and 2.6 seconds, respectively.

Comprehensive damage/ground-motion studies by Trifunac and Brady (1975) and by Trifunac and Westermo (1977) have provided evidence that three interrelated parameters, the amplitude level, the duration, and the frequency of the ground shaking, are the important parameters that cause structural damage. Data from the Paguate investigation show that (a) sites that are located on thick surficial deposits have high site response and higher ground motions at greater distances from the seismic source than sites located on or close to bedrock, (b) sites not on bedrock have amplification factors of 5 to 11, (c) building amplifications range from building amplifications of 3 to 6, and (d) there is increased duration of ground motion at high-damage sites. These data and results are not unique, as other earthquake, blast, and building studies have shown similar results (Algermissen and others, 1972, 1973; Borcherdt, 1970; Borcherdt and Gibbs, 1976; Hays, Algermissen, and others, 1978, 1982; Rogers and Hays, 1978; Rogers and others, 1979, 1980; King and others, 1986; Steinbrugge and others, 1981).

CONCLUSIONS AND RECOMMENDATIONS

The seismic data analyses from the Paguate investigation show that (a) sites at greater distances from the source than many other sites in the village have larger and longer duration shaking at several frequencies due to the site ground-motion response, (b) the buildings' structural response to the induced ground shaking is within the site-response bandwidth, (c) there is no clear evidence of differential compaction under the foundations of the building at most of the sites, (d) the vertical ground-motion attenuation function used by many investigators and mining companies ($R^{-1.6}$) is suitable for vertical ground-motion attenuation for sites on rock in the Paguate area, and (e) the peak horizontal ground motion in the Paguate area attenuates as $R^{-1.15}$. The analyses of the test shots, building studies, and soil tests strongly suggest that the damage to the buildings in the high response areas was greatly augmented or caused by the vibrations induced by the quarry blasting. The damage to the buildings in the scale-3 grading was probably largely caused or increased by the quarry blasting. The cause of the scale-2-graded damage could not be clearly identified but it is reasonable to assume that the blasting was at least a contributory cause.

The following are recommendations for future blasting for mining, reclamation, and (or) industrial development:

1. We recommend that an attenuation scaling function of $R^{-1.1}$ be used for horizontal ground motion. Test blasts should be set off and monitored.

2. The induced vertical and horizontal ground motions should be monitored at a minimum of at least three sites during blasting operations. Recommended sites are 165, 146, and 202. Monitoring at six sites would be very desirable (recommended sites are 6, 34, 165, 146, 202, and China Town). Pre-event inspections should be made of approximately 20 significant structures (sites 6, 20, 21, 34, 50, 71, 96, 99, 144, 148, 164, 167, 168, 202, 220, 221, 300, 304 and China Town are suggested). If no new damage occurs at the selected buildings and preliminary analysis of the seismic data indicates the ground motion at site 165 does not exceed approximately 0.1 in./s (2.54 mm/s), then the yield of the blasts could be increased until the ground-motion limits are reached. This testing will establish the maximum yield and shot configuration for any particular operation.

3. Changing the natural frequencies of buildings that are more sensitive to the induced ground-motion frequencies should be attempted where practicable.

4. Do not add more stiffening to the buildings unless the induced source frequencies and the natural frequencies of the buildings are taken into account as additional stiffening may aggravate the problem by increasing the building/ground coupling or by changing the natural frequency of the building so that it more closely coincides with the frequency of the seismic ground shaking.

5. Run the blasting operations only when the wind is blowing away from the village both to avoid the overpressures on the flat-roofed houses and to minimize the personnel-disturbing acoustics that usually accompany surface or wall blasting.

6. Repairs to the buildings should be made using native materials with consideration of the natural frequencies of the structure. The owners should understand that newer construction methods will probably require different foundations and an engineered coupling method to integrate the old and new portions of the buildings.

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